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Can the Known Millisecond Pulsars Help in the Detection of Intermediate-Mass Black Holes at the Centers of Globular Clusters?

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We consider the possibility of detecting intermediate-mass ($10^3 - 10^4 M_\odot$) black holes, whose existence at the centers of globular clusters is expected from optical and infrared observations, using precise pulse arrival timing for the millisecond pulsars in globular clusters known to date. For some of these pulsars closest to the cluster centers, we have calculated the expected delay times of pulses as they pass in the gravitational field of the central black hole. The detection of such a time delay by currently available instruments for the known pulsars is shown to be impossible at a black hole mass of $10^3 M_\odot$ and very problematic at a black hole mass of $10^4 M_\odot$. In addition, the signal delay will have a negligible effect on the pulsar periods and their first derivatives compared to the current accuracy of their measurements.

Key words: globular clusters, black holes, pulsars, Shapiro effect

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INTRODUCTION

The question of whether black holes with masses $10^3 10^4 M_{\odot}$ are present at the centers of globular clusters arose in the 1970s as new X-ray observational data became available (see, e.g., Clarket al. 1975). In subsequent theoretical works, the effect of a massive black hole in a dense stellar system on its dynamical and astrophysical properties were discussed and numerical solutions were obtained for some stationary cases (see, e.g., Frank and Rees 1976; Bisnovatyi-Kogan et al. 1980). In addition, for some of the clusters, for example, for the globular cluster M15, the detection of a black hole at its center was reported; subsequently,this report was disproved (for the history of this question, see, e.g., McNamara et al. 2003).

In recent years, evidence for the existence of intermediate-mass blackholes (IMBHs), at least in two globular clusters, ωCen (NGC 5139) and G1 (Mayall II) in the galaxy M31 (Noyola et al. 2006; Gebhardt et al. 2005), has appeared in connection with an improvement in observational optical and infrared instruments. In particular, the black hole in the latter cluster was detected and its mass was determined on the basis of Hubble Space Telescope (HST)photometry and HIRES (Keck telescope) spectroscopy (Gebhardt et al. 2005). The observational data were used to construct the dependence of the mass to-luminosity (M/L) ratio on the distance to the cluster center. This dependence shows that the M/L ratio increases significantly at small cluster radii. This behavior of M/L is difficult to explain by the presence of low-luminosity stellar objects near the cluster center, such as white dwarfs and neutron stars. However, it can be well described in terms of dynamical models for globular clusters with massive ($\sim 2 \times 10^4 M_{\odot}$) central objects (Gebhardt et al. 2005). Apart from the clusters mentioned above, there is circumstantial evidence for the existence of a central blackh ole in the globular clusters 47 Tuc, NGC 6752, and M15 (McLaughlin et al. 2006; van den Bosch et al. 2006). XMM-Newton X-ray observations revealed a black hole with a mass of $\sim 10^3 M_{\odot}$ in a globular cluster of the elliptical galaxy NGC 4472, which, in turn, belongs to the Virgo cluster of galaxies (Maccarone et al. 2007). It is important to note that the IMBHs at the centers of globular clusters in our Galaxy may no manifest themselves in X rays. As was shown by Frank and Rees (1976), the disruption rate of stars by black hole with a mass of $10^3 - 10^4 M_{\odot}$ is low. Therefore, all of the possible methods for detecting these objects in all of the wavelength ranges accessible to observers should be used, because the problem of the existence of IMBHs is important in understanding not only the structure and evolution of globular star clusters but also the evolution of galaxies with central black holes and the formation of such objects.

Note that the above-mentioned circumstantial evidence for the existence of IMBHs has been obtained for massive globular clusters with compact dense cores. The largest number of radio pulsars and Xray binaries have been discovered precisely in these globular clusters. In particular, the globular clusters 47 Tuc and M15 that are suspected to host a central blac khole contain 22 and 10 radio pulsars, respectively (http://www.naic.edu/∼pfreire/GCpsr.html).

The radio pulsars have a remarkable property, a high stability of their pulsed radiation,

which can be used to independently confirm the existence of a central black hole in a globular cluster. If a massive compact object is located near the propagation ray of the signal from the pulsar to the observer, then the flux from the pulsar will be magnified (or, in some cases, attenuated) due to gravitational lensing. However, apart from the flux magnification, a signal time delay will also be observed in this case (Krauss and Small 1991). Both these effects can be used to detect the black holes located at the centers of globular clusters. However, the gravitational lensing of Galactic sources (stars and pulsars) in the gravitational field of such black holes is difficult to observe, since the Einstein-Chwolson radius is fairly small (~ 10 AU), while for the flux from the source to be amplified, the line of sight must pass within this small radius (see, e.g., Zakharov 1997).

The angular distances of the currently known pulsars in globular clusters from their centers are typically a few hundredths of an arcminute, which is much larger than the Einstein-Chwolson angular radius.As will be shown below, the relativistic time delay of the pulsar electromagnetic radiation, called the Shapiro effect, may turn out to be significant in this case. An expression for this effect was derived for an electromagnetic signal propagating in a static, spherically symmetric gravitational field of a point mass by Shapiro (1964). Kopeikin and Schafer (1999) generalized the expression to the case of light propagation in a variable field of an arbitrary moving body.

Wex et al. (1996) showed that the timing of millisecond pulsars can be used in principle to detect and identify massive objects in the Galactic Center region. In this paper, based on the calculations of the above paper, we investigate the possibility of detecting IMBHs at the centers of globular clusters using long-term observations of currently known pulsars located at minimum angular distances from the cluster center. Note that the Shapiro effect was previously suggested to be used as a possible cause of the pulsar glitches (Sazhin 1986), to search for dark-matter objects in the Galaxy (Larchenkova and Doroshenko 1995), to test the general theory of relativity in binary pulsars (Doroshenko and Kopeikin 1995), to probe the structure of the Galaxy, and to search for compact objects(Larchenkova and Lutovinov 2007, Siegel 2008).

FORMULAS AND DEFINITIONS

Following the notation used previously (Larchenkova and Lutovinov 2007), Fig. 1 presents a classical model of gravitational lensing for a point lens (a black hole) with mass M_{BH}. The position of the pulsar (PSR) in the sky relative to the observer (O) is specified by the angle θ_s, while the positions of its images are specified by the angles θ_+ and θ_-, where the '+' and '$-$' signs correspond to the first (+) and second ($-$) images, respectively, and d is the impact parameter of the undeflected light ray. In this case, the Einstein-Chwolson radius is defined by the formula

$$R_E = (4GM_{BH}D_{ds}D_d/c^2D_s)^{1/2}, \tag{1}$$

where c is the speed of light in a vacuum, G is the gravitational constant, D_{ds} and D_d are the distances from the pulsar to the black hole with mass M_{BH} and from the black hole the observer, respectively, D_s is the distance from the pulsar to the observer, and $D_s = D_{ds} + D_d$ (the formula for the radius R_E was first derived by Einstein (1965, vol. 2) for $D_{ds} \gg D_d$; Eq. (1) in the commonly used form can be found, e.g., in Vietri and Ostriker (1983)). Note that when the pulsar and the black hole are located in the same globular cluster, $R_E \propto D_{ds}^{1/2}$ with a high accuracy, since the typical size of globular clusters (several tens of parsecs) is much smaller than the distance from these clusters to the observer (several kpc). In general form, the dependence $R_E(D_{ds})$ and its typical values are presented in Fig. 2 for two black hole masses, $M_{BH} = 10^3$ and $10^4 M_\odot$.

The angular distance between the two images, (+) and (−), is defined as (Refsdal 1964; Turner et al. 1984)

$$\Delta\theta = \frac{R_E}{D_d}\sqrt{f^2+4}, \tag{2}$$

where f is the dimensionless impact parameter, $f = d/R_E$. For example, the angular distance between the images for pulsars in the globular cluster M15 ($D_d = 10.2$ kpc and we set D_{ds} equal to ~ 3 pc, which corresponds to the typical radii r_h within which half of the cluster mass is concentrated) is $\Delta\theta = 1.533 \times 10^{-5}\sqrt{M_{BH,M_\odot}}\sqrt{f^2+4}$ arcmin, where $M_{BH,M_\odot}$ is the black hole mass in solar masses.

Apart from the appearance of two images in the plane of the gravitating body, flux magnification and a signal time delay must also be observed in the classical model of gravitational lensing. The former is specified by the formula (Refsdal 1964; Wex et al. 1996)

$$\mu_{+,-} = \frac{1}{4}\left[\frac{f}{(f^2+4)^{1/2}} + \frac{(f^2+4)^{1/2}}{f} \pm 2\right]. \tag{3}$$

It follows from Eq. (3) that the contribution from the second (−) image to the total brightness is small ($\leq 3\%$) even at $f \geq 2$ (below, we will show that the value of this quantity is much higher for the known pulsars) and this image is too faint to be observable. All of the subsequent reasoning refers only to the first (+) image.

For a spherically symmetric Schwarzschild lens, the signal delay can be expressed as (see, e.g., Krauss and Small, 1991)

$$\tau_{+,-} = \frac{2GM}{c^3}\left[\frac{4}{(\sqrt{f^2+4} \pm f)^2} - \ln(\sqrt{f^2+4} \pm f)^2\right] + const \tag{4}$$

where the first and second components reflect the geometric and relativistic time delays, respectively. The delay depends on the impact parameter, which, in turn, varies with time due to the relative motion of the pulsar and the black hole:

$$f = \frac{d}{R_E} = \frac{d_m}{R_E}\sqrt{1 + \left(\frac{v_\perp}{d_m}\right)^2 (t - T_0)^2}.$$

Here, $v_\perp$ is the pulsar velocity relative to the black hole projected onto the plane of the sky, d_m is the minimum impact parameter, t is the current observation time, and T_0 is the time of the closest approach. Thus, the change in delay $\Delta\tau = \tau(t) - \tau(t_0)$, where t_0 is the time at which the observations begin, is a measurable quantity. In Fig. 3, $\Delta\tau$ is plotted against the observation time for the minimum impact parameter $d_m = 10^4$ AU (below, we will show that the observed pulsars in globular clusters are located at similar or larger distances from their centers), the velocity $v_\perp = 30$ km s^{-1} (a typical velocity of globular-cluster stars), $t_0 - T_0 = 5$ yr, and two black hole masses, $M_{BH} = 10^3$ and $10^4 M_\odot$. We see that the maximum signal delay in this case is small, ~ 100 ns and ~ 1 μs, respectively.

KNOWN PULSARS IN GLOBULAR CLUSTERS

Let us now use the above reasoning and formulas to assess the observability of the delay of a signal as it passes near an IMBH for several known pulsars detected in globular clusters. For this purpose, we took the pulsars from Freire's catalog (http://www.naic.edu/∼pfreire/GCpsr.html) closest to the centers of the globular clusters suspected to host black holes. Assuming that the pulsar is located behind the cluster center at a distance of 3 pc, its transverse velocity is 30 km s^{-1}, and the observation time is 5 yr, we calculated the maximum relative delay of its signal as it passed near a black hole with masses $M_{BH} = 10^3$ and $10^4 M_\odot$ for each pulsar ($\Delta\tau_3$ and $\Delta\tau_4$, respectively). The pulsar parameters (the offset – the angular distance between the pulsar and the cluster center) and the results of our calculations are given in the table.

We see from the table that at the currently achievable accuracy of determining the pulse arrival time (PAT) (~ 50 ns for bright pulsars), the observation of the signal time delay for the known millisecond pulsars as their signals pass near the black holes at the centers of the corresponding globular clusters is not possible at a black hole mass of $10^3 M_\odot$ and is very problematic at a black hole mass of $10^4 M_\odot$ even for pulsars close to the cluster center (e.g., B2127+11D or J0024-7204O). A two-fold increase in the duration of observations, to 10 yr, leads to a significant increase in the observed relative signal delay, which can already be detected by currently available instruments. It should be noted that the low-frequency noise due to the motion of globular-cluster stars will have a significant effect on the detectability of single pulse delay events related to the passage of the pulsar signal near a massive black hole (for more detail, see Kopeikin 1999; Larchenkova and Kopeikin 2006).

Effects of the Pulsar Signal Delay on the Observed Periods and Their Derivative

Let us consider how the time delay of the pulsar signal as it passes near a black hole will affect the observed pulsar period and its first derivative and whether a conclusion about the

presence of an IMBH at the cluster center can be drawn from their measurements for the pulsars known to date. For this purpose, we will use reasoning similar to that in Wex et al. (1996). The observed pulsar period P at time t_1 is related to the intrinsic pulsar period P_i as

$$P \simeq P_i + \frac{d\tau}{dt}(t_1). \tag{5}$$

As was noted above, only one (+) image is observed in the case of "weak lensing" ($f \gg 1$) and the geometric delay is negligible (see Eq. (4)). In this case, the time delay is determined only by the Shapiro effect and can be written as (Larchenkova and Doroshenko 1995)

$$\tau_{+} = -\frac{2GM}{c^3}\ln\left(1+\left(\frac{v_{\perp}}{d_m}\right)^2(t-T_0)^2\right). \tag{6}$$

Substituting Eq. (6) into (5) and searching for a maximum of the derived function, we find (Wex et al. 1996)

$$\max\left|\frac{P}{P_i}-1\right| \simeq \frac{2GM}{c^3}\frac{v_{\perp}}{d_m}. \tag{7}$$

For the pulsar B2127+11D from the table, which is closest to the center of the globular cluster M15, the maximum changes in pulsation period are

$$\max\left|\frac{P}{P_i}-1\right| \simeq 1.7\times 10^{-13} \;\; and \;\; 1.7\times 10^{-12}$$

for a black hole mass of 10^3 and $10^4 M_{\odot}$, respectively. The typical accuracies of measuring the periods of millisecond pulsars in globular clusters[1] are several orders of magnitude lower than the above estimates of the maximum change in pulsar period, which, in addition, can be achieved over a disproportionately long time of source observations ($\sim 10^3$ yr).

Let us now consider how the signal delay affects the first derivative of the pulsation period. Let again $\dot{P}$ be the measurable rate of change in pulsar period and $\dot{P}_i$ be the intrinsic change in period. Using the same approach as that for the pulsation period, we find in general form that (Wex et al. 1996)

$$\max\left|\frac{\dot{P}-\dot{P}_i}{P_i}\right| \simeq \frac{4GM}{c^3}\left(\frac{v_{\perp}}{d_m}\right)^2, \tag{8}$$

and for the pulsar B2127+11D

[1]http://www.atnf.csiro.au/research/pulsar/psrcat

$$\max \left| \frac{\dot{P} - \dot{P}_i}{P_i} \right| \simeq 5.8 \times 10^{-24} \mathrm{c}^{-1} \quad and \quad 5.8 \times 10^{-23} \mathrm{c}^{-1}$$

at a black hole mass 10^3 and $10^4 M_\odot$, respectively. These values are again several orders of magnitude lower than the typical accuracies of measuring the first derivative of the millisecond pulsar period. Thus, the effect of an IMBH on the periods and their derivatives for the known millisecond pulsars in globular clusters is too weak to be detected by currently available instruments.

A PULSAR IN A GALAXY BEHIND A GLOBULAR CLUSTER

In conclusion, let us consider the hypothetical case where a millisecond pulsar is located behind a globular cluster at large (several kpc) and small angular distances from the cluster center. Clearly, the probability of such a case is low. Nevertheless, there are observational examples of such a mutual arrangement of objects even now (in particular, the pulsar J1748-2446B, later renamed as PSR J1744-2444, in the globular cluster Ter 5, http://www.naic.edu/∼pfreire/GCpsr.html). For the subsequent estimates, we will assume this angular distance to be the same as that for the pulsar B2127+11D ($0.019'$) and the distance between the globular cluster (M15) and the pulsar to be 3 kpc (i.e., the pulsar is located somewhere in the halo, at the edge of the Galaxy). We see from Fig. 2 that the Einstein-Chwolson radius for such distances increases to several hundred AU. For our estimate, we will take the velocity of the halo and Galactic objects to be $\sim$ 200 km s^{-1}. The maximum relative signal delay recorded over 5 yr is then ~ 2 μs for a black hole mass of $10^3 M_\odot$ and an order of magnitude larger for a mass of $10^4 M_\odot$. Note that the significant increase in signal delay depends weakly on the distance between the globular cluster and the pulsar but is related to considerably higher velocities of the Galactic objects than those of the globular-cluster objects. In this case, the effect of the delay on the pulsation period will still be weak due to the large minimum impact parameter d_m compared to $v_\perp(t - T_0)$.

CONCLUSION

We considered the possibility of using long-term PAT observations for the known millisecond pulsars in globular clusters to detect intermediate-mass ($10^3 - 10^4 M_\odot$) black holes presumably located at their centers.

- The maximum signal delays over 5 years of observations were estimated for several pulsars closest to the centers of the corresponding globular clusters.

- The detection of such a time delay by currently available instruments for the pulsars known to date is not possible for a black hole mass of $10^3 M_\odot$ and very problematic for a black hole mass of $10^4 M_\odot$.

- The pulse delay will have a negligible effect on the pulse periods and their first derivatives compared to the current accuracy of their measurements.

Nevertheless, note that using precise millisecond pulsar timing methods in future (with an improvement in the resolution and sensitivity of instruments, the detection of pulsars at angular distances of a few fractions of an arcsecond from the globular cluster centers, the detection of Galactic pulsars behind globular clusters, a proper analysis of the low frequency noise, etc.) may turn out to be one of the few tools for direct detection of IMBHs at the centers of globular clusters.

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Table 1: Spatial characteristics of the pulsars at minimum distances from globular cluster (GC) center and signal time delays

PSR (GC)	Distance to GC, kpc	r_h, pc	offset, arcmin	d_m, AU	$\Delta\tau_3$, ns	$\Delta\tau_4$, ns
J0024-7204O (47 Tuc)	4.1	3.33	0.06	14762	45	450
J1748-2446C (Ter 5)	10.3	2.49	0.17	105070	0.9	8.9
B1745-20 (NGC6440)	8.4	1.42	0.04	20162	24	240
J1750-3703D (NGC6441)	11.7	2.18	0.05	35103	8.0	80
B1820-30A (NGC6624)	7.9	1.88	0.05	23702	17.5	175
J1910-5959B (NGC6752)	4.0	2.72	0.10	24002	17.1	171
B2127+11D (M15)	10.2	3.18	0.019	11743	71	710

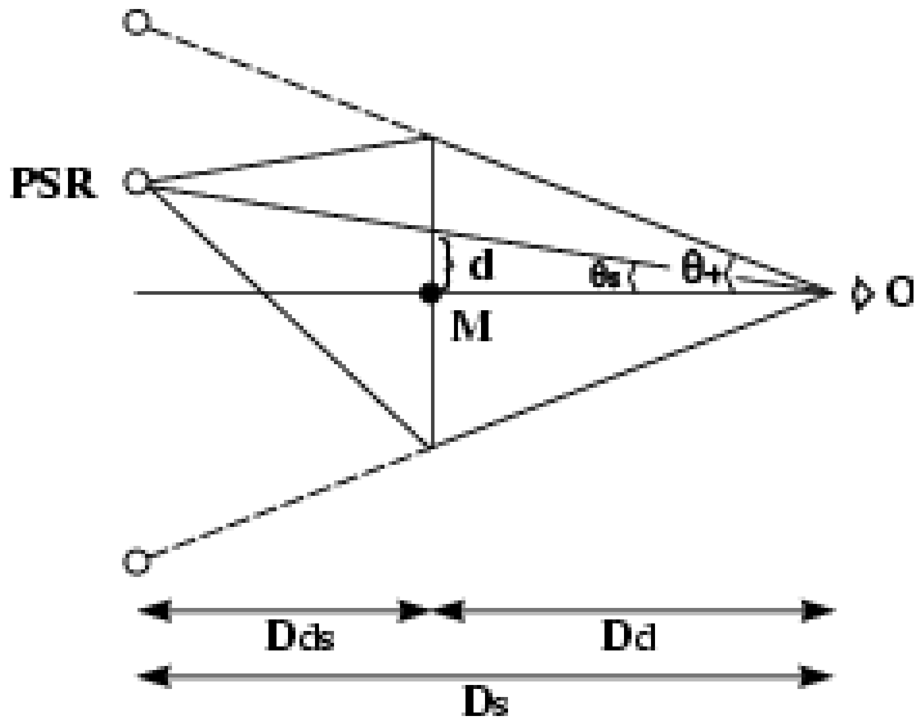

Fig. 1: Geometry of the problem under consideration: O is the observer, PSR is the pulsar, and M is the black hole. For the remaining notation, see the text.

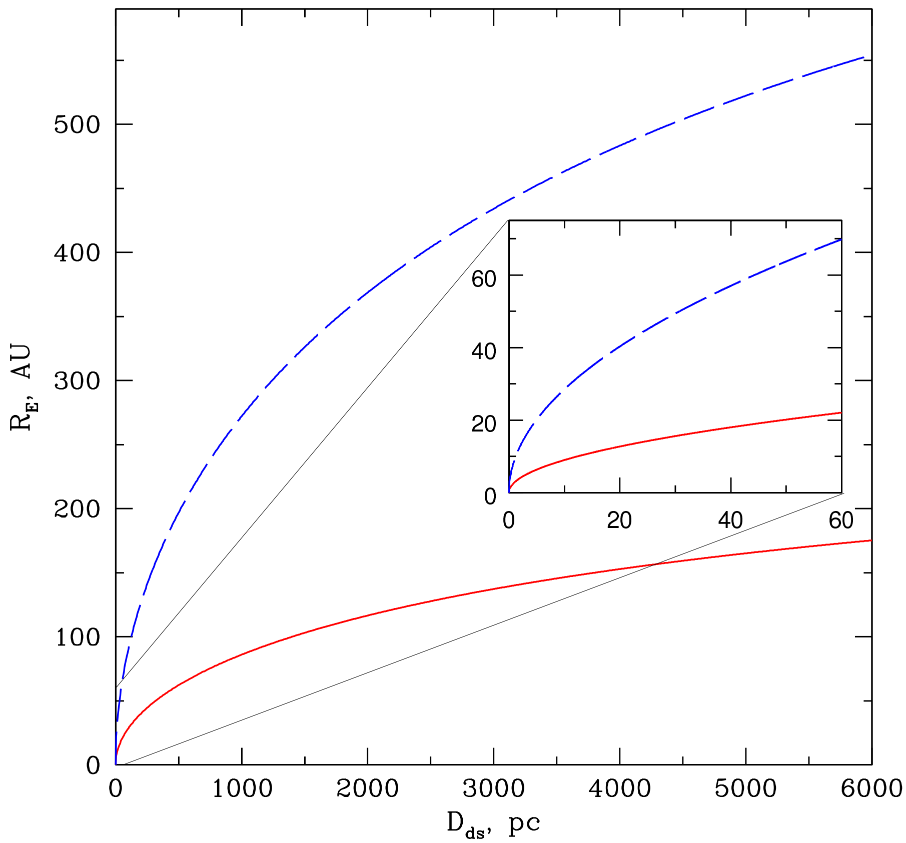

Fig. 2: R_E **versus distance between the black hole and the pulsar: the black hole mass is** $10^3 M_\odot$ **(solid line) and** $10^4 M_\odot$ **(dashed line).**

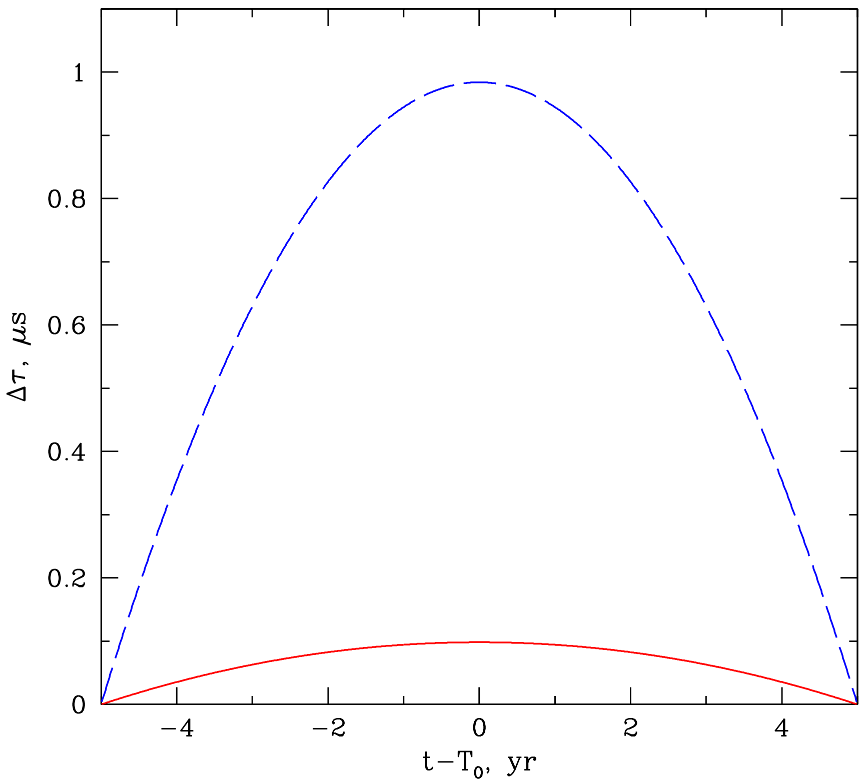

Fig. 3: Relative signal delay $\Delta\tau$ versus time tT_0 (in years) for two central black hole masses, $M_{BH} = 10^3 M_\odot$ (solid line) and $10^4 M_\odot$ (dashed line).